

## Fabrication and testing of large steering mirrors for a scanning lidar

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Large, inexpensive scanning mirrors for a lidar have been designed and built out of common float glass mirrors and aluminum honeycomb. The flatness of the scanning mirrors has been characterized with a modified Foucault knife-edge test. The peak-to-peak surface slope error over the entire surface of the mirrors was found to be less than 1 mrad, with slope errors of 0.15 mrad over small areas. This performance was sufficient for use of the mirrors in a scanning CO<sub>2</sub> lidar system that uses direct detection.

*Key words:* Mirrors, lidar.

Monostatic lidar systems are most often used in a fixed orientation. Scanning a lidar in elevation to produce two-dimensional atmospheric cross sections can be performed either by placing a steerable steering flat in front of the transmitter-receiver or by placing the entire lidar on a gimballed yoke. Either of these solutions becomes more expensive and unwieldy as the aperture size of the receiver telescope increases. Because the steering flat must be larger than the receiver aperture diameter, conventional mirrors become excessively heavy and expensive when the receiver aperture is large.

A design for inexpensive, lightweight steering mirrors has been developed for use with a CO<sub>2</sub> lidar system operating at 10.6  $\mu\text{m}$ . The lidar uses an 18-in.-diameter receiving telescope of Newtonian design and is installed in a laboratory on the top floor of a building at the University of Arizona. The telescope is pointed vertically through a hatch in the roof of the building. The outgoing laser beam is coaxial with the receiver and is reflected off a mirror mounted in back of the telescope diagonal mirror. As shown in Fig. 1, two 24 in.  $\times$  32 in. (61 cm  $\times$  81 cm) steering flats are used to perform elevation scanning. The mirror directly above the telescope is normally fixed at an angle of approximately 45°, and the second mirror rotates on a horizontal axle to perform elevation scanning. The first mirror can be rotated to a horizontal position for focusing and alignment of the telescope. Conventional optical-quality flats of this

size would be several inches thick, weigh approximately 100 kg, require massive support structures, and cost many thousands of dollars. The lidar uses incoherent detection, so the surface flatness requirements on the steering mirrors are much less restrictive than for a coherent CO<sub>2</sub> lidar or other system in which diffraction-limited performance is required. Given a system field of view of 6 mrad, a surface slope tolerance for each steering mirror of 1-mrad peak to peak was derived. A design for the mirrors that uses ordinary 1/4-in. float glass mirrors, yet still maintains adequate surface flatness, has been developed.

Both mirrors (and their support structures) are of identical design. Each mirror is mounted to rotate on an axle through the centerline of the mirror. The mirror and its support must be rigid enough not to sag as they rotate off vertical. A stiff, light structure was fabricated with a 3.81-cm-thick slab of aluminum honeycomb<sup>1</sup> with a 1/4-in.-front-surface float glass mirror on one side and a sheet of ordinary 1/4-in. float glass on the other side [see Fig. 2(a)]. The honeycomb is available in 1.21 m  $\times$  2.43 m sheets in various thicknesses. The thickness of the honeycomb slab is controlled to 0.002 cm or better in the manufacturing process. The mirror structure was fabricated on a granite surface plate. The float glass mirror was placed face down on the surface plate, the back was coated with a structural epoxy,<sup>2</sup> and the honeycomb slab was then placed on it. An aluminum bar with a rectangular cross section was placed across the center of the mirror to act as an axle [see Fig. 2(b)]. One side of the float glass plate was coated with a layer of epoxy and placed on top of the honeycomb to form a sandwich. Weights were placed on top of the sandwich structure, forcing the mir-

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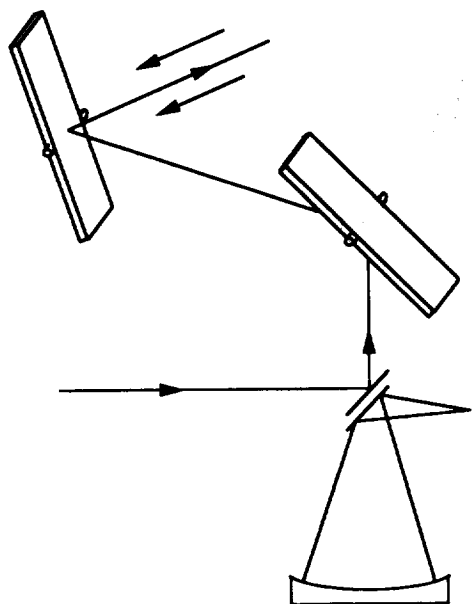


Fig. 1. Layout of the lidar receiving telescope and the scan mirrors.

rored surface to conform to the surface plate, and the sandwich was left to cure. The result was a structure 5.08 cm thick and weighing only approximately 15 kg. A light frame constructed of aluminum, covering the edges and the rear surface of the mirror, was then attached to the axle. The frame acts to protect the mirror from the environment and permits a cover to be placed over the reflective surface when it is not in use but does not provide structural support. The inherent stiffness of the honeycomb mirror structure prevents sagging. The mirrors exhibited no gross surface curvature or sagging when rotated to a horizontal position. Bowing because of thermal

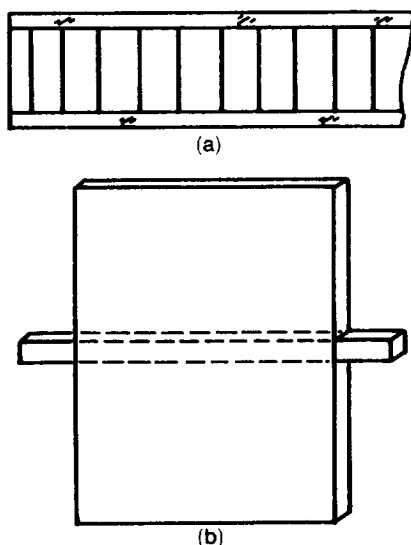


Fig. 2. Scanning mirror construction: (a) cross section of the mirror showing an aluminum honeycomb slab with a float glass mirror on top and an uncoated float glass plate on the bottom, (b) mirror mounted on an axle.

effects is minimized by the use of glass plates of equal thickness on either side of the honeycomb.

The mirrors, mounted in their frames, were tested with a Foucault knife-edge test,<sup>3</sup> which provided a simple, yet sensitive, method of measuring mirror flatness. The test used an astronomical-quality 17.5-in. parabola having an 80-in. focal length to collimate the light source. Initially the surface figure of the parabola was tested with the knife-edge at its center of curvature. The figure error of the parabola was determined to be less than  $\lambda/4$  and of much higher quality than the steering mirrors to be tested. The test setup used with the steering mirrors is shown schematically in Fig. 3. We then analyzed the pattern of shadowing produced by the knife edge to determine the surface slope errors of the test piece. The slope of the region of the test surface at the shadow boundary can be simply related to the displacement of the knife edge from the optic axis of the collimating mirror:

$$\Delta\theta = \Delta y/f, \quad (1)$$

where  $\Delta\theta$  is the surface slope and  $f$  is the focal length of the collimating mirror. The light source and the knife edge were mounted together, so that  $\Delta y$  is the displacement of both the knife edge and the light source from the optic axis. The knife edge was positioned with a micrometer stage having a precision of 0.002 cm. The test was sensitive enough to detect easily surface slope changes of 0.05 mrad (corresponding to a translation of 0.010 cm).

The knife-edge test on the two mirrors that were fabricated showed peak-to-peak slope variations of 0.5 mrad over one mirror and of 0.9 mrad for the other mirror. Figure 4 shows sketches of the shadow boundaries at various knife-edge locations for the better of the two mirrors. The maximum slope in one direction was defined as zero, so that all measured slopes are positive. The larger slope variation in the one mirror was due to the presence of a large wrinkle in the surface approximately 20 cm long and a few centimeters wide near the center of the mirror, which apparently was not pressed out during the bonding. Outside this area, the flatness was comparable with the other mirror. The patterns shown in Fig. 4 can be used to compute the surface area of the tested region of the mirror that has slope errors less than a certain value. Figure 5 compares the slope errors of the two mirrors in terms of fractional enclosed area, similar to a radial encircled energy

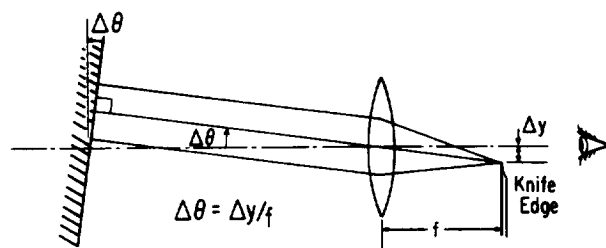


Fig. 3. Knife-edge setup used to test the scan mirrors.

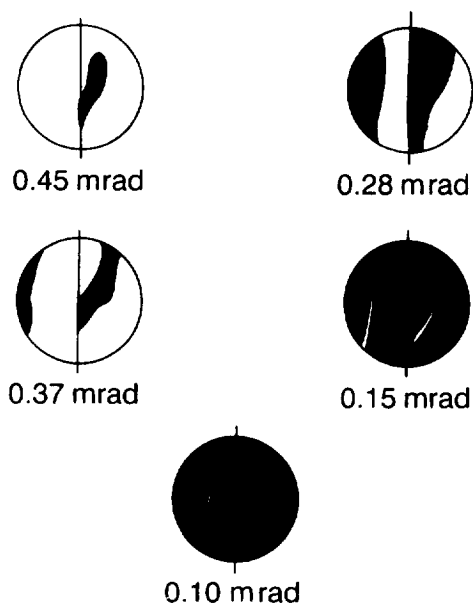


Fig. 4. Shadow patterns produced by a knife-edge test of a 17.5-in. region of the mirror surface. The relative surface slope at the shadow boundary is given at bottom of each sketch.

diagram. Both mirrors have approximately 0.4-mrad surface slope error over most of their surface, with small areas contributing much larger errors.

Small-scale ripples that appear to be a characteristic of float glass were observed in both mirrors. Even over areas as small as  $6.5 \text{ cm}^2$ , the peak-to-peak slope variation was measured to be 0.15 mr. This roughly corresponds to a surface error of 2 waves/cm, which is the typical surface flatness tolerance for this type of glass. A type of Pyrex sheet known as twin-ground Pyrex, which has had these small-scale ripples polished out, is available. This type of glass should be flatter but is significantly more expensive and may have stability problems related to the relief of surface stresses created during the polishing process.

The mirrors have now been used successfully for several years in a harsh desert environment having diurnal temperature fluctuations of up to  $20^\circ\text{C}$ ,

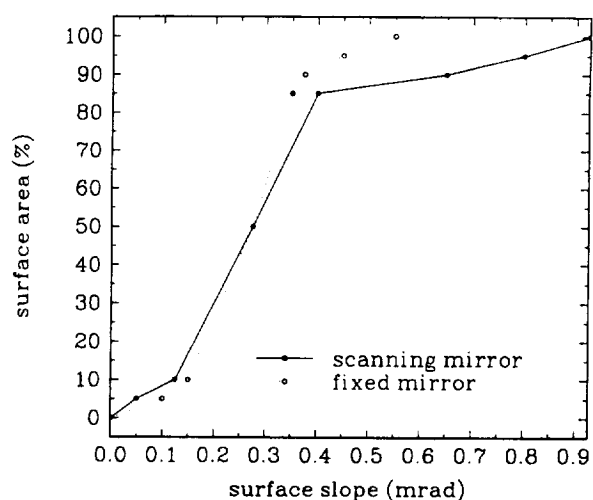


Fig. 5. Cumulative distribution of the surface slope derived from the knife-edge tests.

where summertime temperatures can reach  $44^\circ\text{C}$  in the shade. A recent measurement on the fixed mirror showed it had developed a lengthwise sag of a little over 1 mrad but overall had maintained its structural integrity. This sag increases the background illumination detected by the receiver and decreases performance somewhat, but it is not a serious degradation. The materials used to fabricate the mirror are cheap enough that the mirrors could be replaced every few years.

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#### References and Notes

1. Type CR III-ACG-1/4-5.2, Hexcel Co., Casa Grande, Ariz.
2. Scotchweld structural adhesive, type 2216A/B, 3M Corp., Minneapolis, Minn.
3. D. Malacara, *Optical Shop Testing* (Wiley, New York, 1978), pp. 231-253.

